Review of nitrogen inputs to beaches from marine sources

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Aim. To undertake a literature review to nitrogen inputs to beaches, relevant to Cemlyn Bay.

1. Overview

Beaches are widely recognised to be a relatively low-nutrient system (in marine terms), lacking primary producers. They are a trophic-recipient system, receiving nutrients from the sea. Beaches and other terrestrial coastal systems such as small islands have long been recognised to receive a large subsidy of nutrients from the marine environment (Anderson and Polis, 1999; McLachlan and Brown 2006). There is a strong bias in the literature to areas where there are large quantities of macroalgae deposited on beaches, primarily from areas with offshore kelp forests such as southern California and South Africa. There are a few studies on Mediterranean systems. Most studies appear to focus on sandy beaches, with no studies found which specifically mentioned shingle beaches.

2. Sources of marine-derived nutrients to beaches

There are multiple potential sources of nutrients from the sea to beaches. These include nitrate aerosols salt spray and nutrients in sea foam (Jones et al. 2002). They also include organic material deposited onto beaches by the sea such as macroalgae, carrion (i.e. dead animals), planktonic organisms, and other material such as larger plant remains (branches, seeds, tree trunks) and man-made materials (Colombini and Chelazzi, 2003). Of these, there has been considerable research on the trophic contribution of macroalgae to beaches, and this review draws together much of this evidence. There has been very little work on other components which contribute to nutrient transfer to beaches.

3. Quantities of macroalgae deposited on beaches

Macroalgae deposits on beaches are highly spatially variable, ranging by several orders of magnitude along the same coastline (Dugan et al. 2003; Dugan et al. 2011; Liebowitz et al. 2016). Deposition of wrack is also seasonally variable, depending on the life cycle of the main donor species, and seasonality of storms which uproot or damage growing seaweed (Liebowitz et al. 2016).

The amount of seaweed deposited is highly dependent on presence of nearby donor sources e.g. kelp beds, in combination with transport patterns of local currents (Dugan et al. 2011; Liebowitz et al. 2016). Some studies suggest that the type of beach may also play a role in capturing floating seaweed, with higher wrack deposition in pocket beaches compared with long beaches (Barreiro et al. 2011, Duong and Fairweather 2011). However not all studies show this.

Beaches are linear features, and the consensus used in reporting quantities of beach macroalgae is biomass (wet weight) per linear metre of beach. Some studies also report the area covered with macroalgae as a percentage of total beach area. Typical annual values of biomass on beaches from the literature are summarised in Table 1 below. A typical example of daily wrack input among these studies is 0.1 – 5.6 kg wet weight /m/day on Californian beaches (Dugan et al. 2011).

Table 1. Ranges in biomass of macroalgae on beaches and calculated N content within that biomass.

Annual wrack deposited (wet weight, kg /m/yr)		Nitrogen in wrack (kg N/m/yr)				
Low	High	Low	High	Mid-Pt	Study location	Authors
360	2900	0.72	5.8	3.26	W. Australia	Hansen 1984, cited by Kirkman and Kendrick 1997
550	2660	1.1	5.32	3.21	Patagonia	Piriz et al. 2003
620	840	1.24	1.68	1.46	S. California	Dugan et al. 2011
	2000		4	4	S. Africa	Griffiths et al. 1983
1200	2179	2.4	4.358	3.379	S. Africa	Stenton-Dozey and Griffiths, 1983
	473		0.946	0.946	S. California	Hayes 1974
				1.4	S. Africa	McLachlan and McGwynne 1986
				4.38	S. Africa	Koop et al. 1982

4. Corresponding quantity of N input in macroalgae on beaches

While a number of studies have looked at nutrient cascades within this trophic system, they primarily focus on the number of invertebrates supported by beach-cast wrack and higher trophic levels such as birds which in turn feed on the invertebrates. Relatively few quantify the amount of N deposited.

We used published wet:dry weight conversion of 10:1 and a mean nitrogen content of 2% (Reed et al. 2008) for giant kelp to calculate approximate nitrogen loads for the biomass values reported in Table 1. We recognise that conversion factors may be different for other species, but this approach allows us to estimate nitrogen loads for these studies. A few studies did provide estimates of the N loads: Dugan et al. (2011) estimated around 1 kg N/m/yr for a particular beach. The values in Table 1 are our estimates based on an average across beaches from that study. McLachlan and McGwynne (1986) report 1.4 kg N/m/yr in red macroalgal wrack, and Koop et al. (1982) report a value of 4.4 kg N/m/yr.

5. Nitrogen from other sources (animals, marine aerosols)

A few studies report estimates of N inputs from dead animals, primarily larger animals such as birds, marine mammals etc. We do not report these here as their occurrence is highly stochastic. However, we found one study that reported inputs from smaller organisms, potentially of greater relevance. Kemp (1986) calculated the quantity of N input from a mass stranding of Cnidaria *Velella velella* (By-the-wind sailor) which amounted to 0.347 kg N/m.

The majority of N in marine aerosols is water soluble organic nitrogen or in the form of ammonium compounds (Altieri et al. 2016). We did not find any studies which estimated N deposition from saltspray, aerosols or sea foam. While Jones et al. (2002) concluded in their short review that there was potential for this to occur, also stated by Polis et al. (2004), it is not easily quantified.

6. How much N is retained on the beach or moved inland ?

While macroalgae inputs to beaches can be considerable, a key question is how much of this energy transfer remains on the beach or is transported inland, and how much is returned to the sea. The majority of the N input in the form of wave-deposited detritus will lie between low and high water, but marine debris is carried high up the beach on spring tides, and a proportion is moved/blown inland. The proportion moved inland by wind or through trophic transfers via the food web is unknown, but is likely to be a relatively small fraction of the total inputs. By contrast, aerosols and sea spray will influence a much greater extent than just the intertidal zone.

Beaches clearly do not accumulate organic matter (McLachlan and McGwynne 1986), therefore all of the organic material deposited on beaches must be processed in some way. The consensus seems to be that the majority is returned to the sea through decomposition by herbivores and microbial activity. Dugan et al (2011) studied relationships between nutrient concentrations in nearshore waters, the beach sediment and macroalgae. They found significant correlations of dissolved inorganic nitrogen (DIN) concentrations in the surf-zone and in interstitial water on the intertidal beach area with the biomass of wrack on Californian beaches, suggesting that this was due to export of nutrients from mineralised seaweed.

Consumption rates of macroalgae debris by (sandy) beach detritivores are high, ranging from 1% to 90% of deposited material per day (Mews et al. 2006; Lastra et al. 2008). On an annual basis, Griffiths et al. (1983) estimate that 71% of the macroalgae deposition to a South African beach was consumed by herbivores.

However, as noted above, some seaweed material is blown inland, or is transported high up the beach zone by storms and subsequently becomes incorporated into terrestrial plant communities. Other pathways by which nutrients do not directly return to the sea are through denitrification, transfers to higher trophic levels by terrestrial invertebrates and vertebrates such as rodents and birds feeding on beach invertebrates, and direct uptake of mineralised nutrients by plants such as *Crambe maritima* growing on or near the strandline. We found no literature quantifying these types of nutrient transfers.

7. Scaled estimates of marine inputs

It is difficult to translate the literature figures of N input from seaweed biomass directly to potential inputs to the shingle bar at Cemlyn. Total seaweed biomass input at Cemlyn is likely to be lower than in the kelp-forest dominated studies elsewhere. A number of calculations are required to convert biomass per linear metre of beach into a unit area load (e.g. per ha per year). A critical assumption here is how far that material is distributed inland (see section 6). If the assumption is made that any of the material that is redistributed by wind or animals remains on the shingle bar, and the bar is of average 50m width (Sneddon and Randall 2003), then that allows a conversion per unit area. We stress that in the absence of specific information, this assumption is based on expert judgement.

Therefore, based on a series of assumptions, we can estimate potential nutrient inputs from macroalgae. Assuming a conservative input of around 100 kg wet weight seaweed /m/yr, this would equate to 0.2 kg N/m/yr. If around 5% of that was not returned to the sea and remained accessible to the terrestrial system, spread over an inland area of the 50m wide shingle bar, that would equate to an input of 2 kg N/ha/yr.

This estimate excludes potential inputs from saltspray and sea foam and seabird guano, which are unquantified, but can be considered as primarily natural inputs (but see Conclusions section below where potential anthropogenic modification of these natural inputs can occur). Nonetheless, it seems rather low in comparison to estimates of net N inputs to estuarine saltmarshes of 87 kg N/ha/yr particulate N and 74 kg N/ha/yr as dissolved organic N in the USA (Boorman and Hazelden 2012).

Our estimate comes with very high uncertainty, due to the multiple assumptions that have had to be made. It should be stressed that making different assumptions in the calculations used for Cemlyn could alter the estimates significantly.

8. Conclusions

There is insufficient knowledge on i) the quantities of macroalgae deposited on beaches on Anglesey, ii) the quantity of organic material that is not returned to the sea but becomes available to terrestrial plants, and iii) the quantities of N in sea spray and foam. Basic data on all these aspects is required to make a more reliable estimate of the marine deposition of nutrients to terrestrial coastal plant communities.

It is important to note that the N inputs discussed in this note are natural inputs, and the plant assemblages in the coastal systems are adapted to them. It is for this reason that the critical loads for these habitats are either relatively high, or the habitats are not considered responsive to N. Note also that these specific natural coastal N inputs are not included in the CBED nitrogen deposition data. In this context, the potentially high levels of natural N input are not a cause for concern *per se*. Where anthropogenic inputs are likely to lead to enhancement of these natural N fluxes, for example through eutrophication of coastal waters which might increase nutrient concentrations of sea water and therefore sea foam/salt spray inputs, or productivity of marine algae, this anthropogenic enhancement may lead to alteration of coastal vegetation communities. However, it is not considered likely that the construction phase of the Wylfa Newydd Project will alter N fluxes from the marine environment.

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